ENERGY EFFICIENCY AND ENVIRONMENT

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In this paper, we intent to review and reconsider the concept of efficiency applied to energy systems and processes. It is shown that due to increasing use of energy, we must refine the criterions that serve as objective functions to characterize and optimize systems and processes. Moreover coupling between energy uses and environment appears more and more important. This question starts to be explored : present state of the art is summarized ; some suggestions and perspectives are evoked, particularly the relation to economy, even if the main aspects developed remain centered on the scientific part and technical consequences.

Keywords: energy, environment, economy, efficiency.

1. Introduction

At this time, it appears to everybody that energy is scarce and limited for the common forms. The common forms are fuels, and they are burned in order to produce heat, before to be partially converted mainly in electricity. Consequently are generated pollutants, and among them CO_2 ; the greenhouse effect is today presented as a problem to solve, in the near future. Indeed reduction of CO_2 emission is related to Energy Efficiency : many institutions are proposing research programs in the field.

For example in France, A.N.R. (National Research Agency) has a program E.E.S.I. (Energy Efficiency in Industrial Systems) ; A.D.E.M.E. has a program for ECOINDUSTRIE (demonstrators with high economical and environmental impacts). C.N.R.S. (National Center for Scientific Research) has a group devoted to Energy Efficiency (GAT 2E) since approximately ten years.

At an European level it is well known, that the 7th Program for Research and Development (7th PCRD) possesses the two aspects Energy and Environment [1, 2]. To summarize, the European regulation is based on three main actions :

a) to reduce with 20 % emission of CO_2, for 2020

b) to produce 20 % of electricity using renewable energies

c) to ameliorate with 20 % Energy Efficiency in any system or process.

The purpose of this lecture is to show how Thermodynamics constitutes a powerful tool to solve the third goal. This has been developed in the past by various authors, among them [3, 4, 5, 6] ; but progress are always done in the field and new books have been recently proposed [7, 8]. It appears that Thermodynamics evolved particularly since the eighties, and new proposals have been developed. The first objective of this paper is to synthesize the new

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tendencies developed for criterions relative to energy efficiency on the basis of Thermodynamics (section 2) ; the criterions are entlightened through simple examples. A second objective is to point up a general methodology in order to optimize systems and processes, using the previous criterions (section 3) ; it results that constraints on the systems or processes play determining role in the optimization procedure and results are fundamentally affected. These conceptual (section 2) and methodological (section 3) aspects are illustrated with some details (section 4) with results obtained for engines (section 4.1) for refrigerating machines and heat pumps (reverse cycle machine) (section 4.2), for combined heat and power systems (C.H.P.) (section 4.3). The last section (section 5) is relative to conclusions and perspectives coming out of this review.

2. Energy Efficiency criterions and Thermodynamics

Thermodynamics is a multidisciplinary field considering all forms of energy [7], in connexion with engineering purpose since the pioneering work of CARNOT [8]. It allows also a multiscale approach starting from the processus or mechanism (local point of view). When evolving from the local situation to the global one, some informations are globalized through "mean" values.

Nevertheless the first law of Thermodynamics indicates that matter and energy are conservative. This implies the corresponding balances, in transient conditions, or in steady state conditions. We will focus in this review on steady state conditions, for example the conditions choosen when designing the system or the process.

The second law of Thermodynamics is relative to the evolution of the system or process, than never can be ideal (or perfect) ; it results irreversibilities. The existence of these intrinsic imperfections, are commonly quantified trough the efficiency concept. CARNOT is the father of this concept.

2.1. Efficiency according to the first law of Thermodynamics

If we focus on energy, as was done by CARNOT, the first definition, that is the most common for energy efficiency is given by :

$$E.E = \frac{U.E}{E.C} \qquad (1)$$

U.E, useful energy

E.C, energy consumption

It is to be noted, that this concept is an extensive one. That is to say, relative to energy extensive quantities. But we have to take care because, the values of these quantities could be local, or global, mean value over time or instantaneous value. Moreover an interesting remark appears if there are more than one useful energy, and (or) more than one energy consumption ; this question will be developed in section 4.

2.1.1. Extension of the concept of first law efficiency

Presently we propose to generalize the definition of efficienciy according to the first law of thermodynamics E_I as :

$$E_I = \frac{U}{C} \tag{2}$$

U, useful effect
C, consumption

U, C must be put in the same S.I. unit in order to get a non dimensional number for E_I ; this number is lower than one. This extension establish clearly a connexion in between matter and energy. A distinction has to be done also between transfer processes and conversion : this will be considered hereafter.

2.1.2. Some simple illustrations

We give hereafter two examples of first law efficiencies, within the hypothesis of steady state situation.

The first one appears on Figure 1, and illustrates the case of mass transfer inside a compressor, an expansion device, or an internal combustion engine.

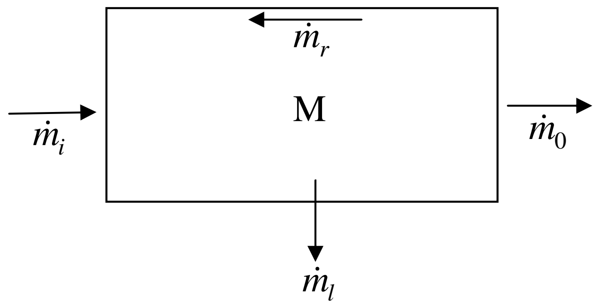

Fig. 1. Mass transfer efficiency

M, represents the mass inside the system at a given instant t, $\dot{m}_i, \dot{m}_0, \dot{m}_l, \dot{m}_r$ are respectively the input, output, loss, and reverse mass fluxes.

Consequently the mass transfer efficiency becomes :

$$\eta_{\mathrm{Im}} = \frac{\dot{m}_0}{\dot{m}_i} = 1 - \frac{\dot{m}_l + \dot{m}_r}{\dot{m}_i} \qquad (3)$$

The second example is relative to an heat exchanger, HEX. Figure 2 represents this HEX

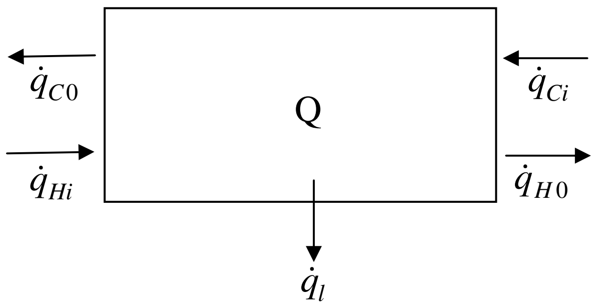

Fig.2. Heat transfer efficiency

t appears on the figure, Q the heat energy inside the system at a given instant t ; $\dot{q}_{Hi}, \dot{q}_{HO}, \dot{q}_{Ci}, \dot{q}_{C0}, \dot{q}_L$ are respectively the hot input, hot output, cold input, cold output, heat loss fluxes.

Consequently depending on the use of the HEX, we can define a heating efficiency for the cold fluid from an absolute point of view

$$\eta_{IH} = \frac{\dot{q}_{C0}}{\dot{q}_{Hi}} \qquad (4)$$

More classically, from a relative point of view, only the heat transferred in the HEX is considered

$$\eta_{IH} = \frac{\dot{q}_{C0} - \dot{q}_{Ci}}{\dot{q}_{Hi} - \dot{q}_{H0}} = 1 - \frac{\dot{q}_L}{\dot{q}_{Hi} - \dot{q}_{H0}} \qquad (5)$$

This second HEX efficiency is an heat transfer efficiency ; Here we see that, if the HEX is an adiabatic one, the corresponding efficiency is one.

The corresponding results could be easily obtained, if we consider a cooling efficiency.

An essential remark is that we don’t include the mechanical energy necessary for the flows (we will see hereafter) : only heat tranfer is accounted for.

We examplifie here only heat transfer efficiencies, but energy conversion efficiencies are also to be considered.

2.2. Efficiency according to the second law of thermodynamics

Here attention is put on the departure of the real systems or processes efficiency from a theoretical limit due to irreversibilities (dissipation of energy).

Energy Efficiency of a system or process from the second law point of view could be defined as a quality factor F_q of the real system or process, by reference to the corresponding theoretical limit.

$$F_q = \frac{E.E\,real}{E.E\,\lim it} \tag{6}$$

It is clear that this concept is a qualitative one ; it focuses on the irreversibilities influence and significance on the system or process energy efficiency.

To illustrate this definition, we consider the simple example of the CARNOT thermomechanical heat engine ; if we globalize all the irreversibilities as a dissipation entropy flux $\dot{s}_i$ under steady state conditions, it comes easily two results :

$$F_q\left(\dot{Q}_0\right) = 1 - \frac{T_{SC}\,\dot{s}_i}{\eta_C\,\dot{Q}_0} \tag{7}$$

$$F_q\left(\dot{w}_0\right) = 1/\left[1 + \frac{T_{SC}\,\dot{s}_i}{\dot{w}}\right] \tag{8}$$

T_{SC}, temperature of the cold sink (thermostat)

$\dot{Q}_0$, heat flux input in the engine (reference)

$\dot{w}_0$, engine power (reference).

So the quality factor of the engine depends on a non dimensional form of the energy dissipation ($T_{SC}\,\dot{s}_i$), but with reference to the E.C ($\dot{q}_0$) or U.E ($\dot{w}_0$). η_C represent the CARNOT efficiency, the theoretical limit of the corresponding case :

$$\eta_C = 1 - \frac{T_{SC}}{T_{SH}} \tag{9}$$

T_{SH}, temperature of the hot source (thermostat).

2.3. Exergetic efficiency

Exergetic efficiency uses the concept of exergy that was introduced first by GOUY and STODOLA. The exergy concept is important because it situates the system in environment. Relative to the reference state corresponding to environment we can define chemical, mechanical, physical exergy. For thermomechanical system in an environment characterized by (P_0, T_0) physical exergy E_x in a state (P, T) is given by :

$$E_x = \left[H(P,T) - H(P_0,T_0)\right] - T_0\left[S(P,T) - S(P_0,T_0)\right] \quad (10)$$

P(T), pressure (temperature) for the state considered
$P_0(T_0)$, pressure (temperature) of the environment (reference)
H, enthalpy of the considered system or process in a given state
S, entropy of the considered system or process in a given state

Commonly the influence of reference temperature alone is consider.
If we represent the reference environment by T_0, it comes :

$$E_x = H - T_0 S - E_{x0} \quad (11)$$

It corresponds for thermomechanical system to the part of energy that can be converted in mechanical energy.
By analogy with (1), we define here an Exergy Efficiency $E_x E$

$$E_x E = \frac{U.E_x}{E_x.C} \quad (12)$$

$U.E_x$, useful exergy
$E_x.C$, exergy consumption

This concept is extensive, but also intensive, as it will be examplified hereafter.

2.3.1. Exergetic efficiency of a refrigerating machine

Figure 3 represents a refrigerating machine or an heat pump fonctionning in a steady state according to a CARNOT reverse cycle.

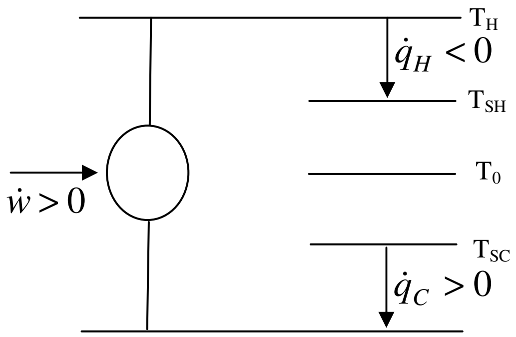

Fig. 3. Schematic analysis of a CARNOT refrigerating machine or heat pump in a steady state

The available exergy on the cycled fluid at the hot side is :

$$\dot{E}_{x_H} = \left(1 - \frac{T_0}{T_H}\right)\dot{q}_H < 0 \qquad (13)$$

The available exergy at the hot sink differs :

$$\dot{E}_{x_{SH}} = \left(1 - \frac{T_0}{T_{SH}}\right)\dot{q}_H \qquad (14)$$

Accordlingly, the available exergy on the cycled fluid at the cold side is :

$$\dot{E}_{x_C} = \left(1 - \frac{T_0}{T_C}\right)\dot{q}_C < 0 \qquad (15)$$

The available exergy at the cold source differs :

$$\dot{E}_{x_{SC}} = \left(1 - \frac{T_0}{T_{SC}}\right)\dot{q}_C \qquad (16)$$

Using the definition (10) applied to the machine (cycled fluid : equation (15)), it comes :

$$E_x.E\,(machine) = \frac{T_0 - T_C}{T_C} . \frac{\dot{q}_C}{\dot{w}} = \frac{COP\,real}{COP(T_0, T_C)} \qquad (17)$$

It is to be noted that in equation (17), COP (T_0, T_C) represents the coefficient of performance of a machine between two thermostats at T_C (fluid cold temperature) and T_0 (ambient temperature).

Using the definition (12) applied to the system (to say the machine in its environment : equation (16)), it comes :

$$E_x.E\,(system)=\frac{T_0-T_{SC}}{T_{SC}}.\frac{\dot{q}_C}{\dot{w}}=\frac{COP\,real}{COP\,(T_0,T_{SC})} \tag{18}$$

It is to be noted that the two exergetic efficiencies (equations (17) et (18), differs from T_C to T_{SC} ; in the common situation of refrigerating machines, $T_{SH} = T_0$. So it comes the particular results :

$$E_x.E\,(system)=\frac{COP\,real}{COP\,\text{lim}\,it}=F_q \tag{19}$$

2.3.2. Exergetic efficiency of a C.H.P. system

This efficiency could be expressed with reference to the cycled fluid, or with reference to the useful external medium (medium temperature, T_u) ; for a heat cogeneration system, $T_u > T_0$, the ambient temperature. Useful exergy flux E_{x_u} can be expressed according to the entropy analysis, when the $\dot{s}_i$ parameter is assumed constant as :

$$\left|\dot{E}_{x_u}\right|=\dot{q}_H\left(1-\frac{T_0T_C}{T_uT_H}\right)-\frac{T_0T_C}{T_u}\dot{s}_i \tag{20}$$

In that case the consumed energy flux at the heat source is given by equation (14), so that energy efficiency results as :

$$E_x.E\left(CHP\,system\right)=\left(1-\frac{T_0T_C}{T_uT_H}\right)/\left(1-\frac{T_0}{T_{SH}}\right)-\frac{T_0T_C}{T_uT_{SH}}\left(T_{SH}-T_0\right)\dot{s}_i \tag{21}$$

T_H, T_C variables appear in equations(20, 21), so that optimization is a consequence of this analysis (section 3).

3. Thermodynamics and optimization

3.1. Optimization of E.E energy efficiency

This optimization remains the one most used today. But we have to review that according to equation (1) :

$$MAX\ E.E=MAX\left(\frac{U.E}{E.C}\right) \tag{22}$$

Consequently $MAX\ E.E$ differs from $MAX|U.E|$ and from $\min|E.C|$. It is why the efficiency at maximum power introduced by CHAMBADAL, NOVIKOV, CURZON and AHLBORN is a fundamental results [10]. But other important optimization appear as $MAX|U.E|$ or $\min|E.C|$. Nowadays it is important to add the release of by-products into the environment, R, that conducts to min R, an ecological criterion ; this will be discussed in section 5 with conclusions and perspectives.

Here we may mainly distinguish in between static optimization relative to design of systems and processes in steady state nominal conditions and dynamic optimization characterized by transient conditions : control – command of the system or process. Parallel considerations could be applied to exergetic criterions and to quality factors.

3.2. Constrained optimizations

The influence of the choice of objective function will be discussed in sections 4 and 5, but we need to mitigate due to constraints ; whatever is the optimization envisaged, physical equations (the first and second law of thermodynamics ; state equation of the cycled fluid ; kinetic equations) represent analytical constraints existing between system variables and parameters. But other constraints could be added because of physical or engineering limitations. These could include finite size, finite time, finite speed, material constraints (maximum pressure and temperature) and finite costs ; environmental constraints are of growing importance also in today's world.

This means that Finite Dimensions Thermodynamics is now a mandatory subject for the purpose of systems or processes optimization. In section 4, we will give examples in the framework of F.D.O.T. (Finite Dimensions Optimal Thermodynamics) of some cases where other constraints are added to the "natural" optimization case [11]: imposed power, imposed heat flux input, imposed engine efficiency, or limitation relative to temperature (intensive variable). For the last case refer to references [12, 13].

4. Illustrations by some obtained results

4.1. Optimization of a CARNOT engine

Results relative to finite heat transfer conductance, with linear heat transfer law are given in the recent reference [11]. It comes from energy efficiency optimization that :

$$MAX\ \eta_I = 1 - \frac{T_{SC}}{T_{SH}} \left(\frac{1+\sqrt{s_i}}{1-\sqrt{s_i}} \right)^2 \qquad (23)$$

with $s_i = \dot{s}_i / K_T$

The CARNOT engine could also be considered differently (from the point of view of Finite Speed) ; the corresponding results are given in reference [14] for a reverse cycle CARNOT machine.

4.2. Optimization of a reverse CARNOT machine

The optimization of reverse cycle machines has been studied since 1986, in the research team through a pioneering work [15]. The work has been developed and completed by review papers : in english [16, 17, 18]. Some papers are centered on particular aspects of optimization ; among them, one of the most recent [19] considers the irreversibility generation analysis of a reversed cycle CARNOT machine using finite speed Thermodynamics.

We propose hereafter a recent model of a double use reverse cycle CARNOT machine [20]. The model is relative to steady state irreversible system, and takes account of finite size constraint through linear heat transfer law : the system is a "thermo-frigo-pump", TFP.

4.2.1. First law criterion for a TFP

It comes from (1) :

$$COP_{ITPF} = \frac{\dot{q}_C - \dot{q}_H}{\dot{w}} = COP_{IMAF} + COP_{IHP} \qquad (24)$$

But it is to be noted that the two useful effects are produced at different temperature levels ; the same holds for MAF or (and) HP with numerous useful effects.

4.2.2. Exergetic criterions

The same demarch as previously allows us to define the exergetic efficiency

$$E_x E = -\frac{\dot{E}_{x_H} + \dot{E}_{x_C}}{\dot{w}} \qquad (25)$$

In the case where the reference is the machine (cycled fluid) it comes :

$$E_x.E_M = \frac{\dot{q}_H \left(1 - \frac{T_0}{T_H}\right) + \dot{q}_C \left(1 - \frac{T_0}{T_C}\right)}{\dot{q}_H + \dot{q}_C} \tag{26}$$

In the case where the reference is the system (machine in its environment) it comes :

$$E_x.E_S = \frac{\dot{q}_H \left(1 - \frac{T_0}{T_{SH}}\right) + \dot{q}_C \left(1 - \frac{T_0}{T_{SC}}\right)}{\dot{q}_H + \dot{q}_C} \tag{27}$$

Optimization of the finite size system, using (26) leads to [20]

$$K_C = \frac{1}{2}\left(K_T - \frac{\dot{s}_i}{\alpha}\right) \tag{28}$$

$$K_H = \frac{1}{2} K_T + \frac{\dot{s}_i}{\alpha} \tag{29}$$

with $\alpha = \sqrt{\frac{\dot{s}_i}{K_T}}$

$$OPT\left[E_x.E_x\right] = \frac{\left(T_{SH} - T_0\right)\left[1 + \sqrt{\frac{\dot{s}_i}{K_T}}\right]^2 - \left(T_{SC} - T_0\right)\left[1 - \sqrt{\frac{\dot{s}_i}{K_T}}\right]^2}{T_{SH}\left[1 + \sqrt{K\frac{\dot{s}_i}{K_T}}\right]^2 - T_{SC}\left[1 - \sqrt{\frac{\dot{s}_i}{K_T}}\right]^2} \tag{30}$$

The influence of the temperatures and irreversibilities through $\dot{s}_i$ is clear in equation (30). If the system becomes an endoreversible one, the Exergetic Efficiency tends to one for a TFP.

4.3. <u>Optimization of a CHP system</u>

Coming back to equation (20), we can obtain, for the finite size system, the conditions corresponding to

$$MAX\left|\dot{E}_{x_u}\right|_{opt} = \frac{K_L\left(\sqrt{T_S}-\sqrt{T_0}\right)\left[K_T\left(\sqrt{T_S}-\sqrt{T_0}\right)-\dot{s}_i\left(\sqrt{T_S}+\sqrt{T_0}\right)\right]}{K_T-\dot{s}_i+4K_L} \quad (31)$$

T_S is given by : $K_L T_S = \dot{Q} + K_L T_0$

Supposing incoming energy flux pure exergy (radiative energy for a solar system or chemical energy for an engine) this corresponds to the first law efficiency at MAX $\left|\dot{E}_{xu_{opt}}\right|$:

$$\eta\left[MAX\left|\dot{E}_{x_u}\right|_{opt}\right] = \frac{1}{\sqrt{T_S}+\sqrt{T_0}}.\frac{K_T\left(\sqrt{T_S}-\sqrt{T_0}\right)}{K_T-\dot{s}_i+4K_L} \quad (32)$$

Complementary results could be find in [21].

A third optimisation could be performed to find the best allocation between thermal losses (K_L) and the total heat conductance K_T, such that $K = K_L + K_T$. The result is :

$$OPT\left[MAX\left|\dot{E}_{x_u}\right|_{opt}\right] = \frac{K}{10}\left(\sqrt{T_S}-\sqrt{T_0}\right)^2 \quad (33)$$

As a partial conclusion, the same methodology is presently developed by our research team for cascad and hybrid systems.

5. Discussion

We have seen in the preceding section that efficiency is a complex concept.

Presently it remains to extend this concept to environmental and ecological situations. New definitions are proposed like Emergy [22], Entransy [23]. We think that the proper use of Exergy [22] or Entropy analysis [24] is probably the most simple and effective way to pursue in direction of ecological criterions.

It seems that the significance of proposed ecological "indicators" are not so clear, for example:

ECOP (Ecological Coefficient of Performance) proposed by UST for an engine :

$$ECOP = \frac{\dot{w}}{T_0\,\dot{s}_t} \quad (34)$$

This is to be compared to ecological function introduced by F. Angulo Brown and Yan ($\dot{E}=\dot{w}-T_0\dot{s}$).

More precisely, Ecological Efficiency ε is related to a pollution index Pg, that is related on a dimensional form to LHV of the fuel according to :

$$\varepsilon = f\left(Pg\right) \tag{35}$$

with $Pg = \dfrac{(CO_2)eq}{LHV}$

$(CO_2)eq$, represents an equivalent concentration of all pollutants. This way seems a promising one, that is well developed in the domain of refrigerating machines (24) through GWP index, and TEWI index.

- extension to resource use assessment studies and L.C.A. Life Cycle Analysis is straight forward, and was proposed in the past as TERE method (Total Equivalent Resource Exergy) : this aspect is now envisaged through the relation in between sustainability and development.

- energoeconomy is a well developed field for engineers. Investment cost and global cost are common objective functions. Extension to exergoeconomy is more recent and promising.

Probably the same demarch could be developed through entropy analysis : it is the goal proposed by the present review ; nevertheless it appears that.

- efficiency could not be considered as an absolute concept. It remains subjective and dependant of the point of view multiplicity (from individual to collective). Consequently a multicriteria optimisation could be performed. But we have seen through examples that added constraints play also an important role and influe significantly the results. So they have to be defined precisely.

Works are in progress all over the world on these questions. Our research time, focuses mainly on developing Finite Dimensions Optimal Thermodynamics (FDOT), a more restricted subject.

We acknowledge all colleagues, who discuss and exchange with us on these subjects ; without them this review was not possible.

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